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Entry Barriers, Competition, and Technology Adoption

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Abstract: There are large differences in income per capita across countries. Growth accounting finds that a large part of the differences comes from the differences in total factor productivity (TFP). This paper explores whether barrier to entry is an important factor for the cross-country differences in TFP. The paper develops a new model to link entry barriers and technology adoption. In the model, higher barriers to entry effectively reduce entry threat, and lower entry threat leads to adoption of less productive technologies. The paper demonstrates that technology adopted in the economy with entry threats is at least as good as the technology adopted in the economy without entry threats. Moreover, the paper presents numerical simulations that suggest entry barriers could be a quantitatively important reason for cross-country differences in TFP and are more harmful to productivity in the countries with monopolists facing inelastic demand.

JEL classification: O11, O43

Key words: entry barriers, technology adoption, total factor productivity

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1 Introduction

Why does output per capita vary so much across countries? This is one of the most important questions in economics. According to the Penn World Tables, GDP per capita in the U.S. is more than 30 times larger than GDP per capita in the poorest ten percent of countries in the world. A large body of research works have found that differences in TFP is the quantitatively most important factor for the cross-country differences in GDP per capita.[1] This raises the question of why poor countries do not use better technologies.

This paper proposes a theory of TFP differences based on cross-country differences in the barriers to setting up a new business. The theory is supported by strong empirical evidence. For example, Djankov et. al. (2002) analyze the data on the regulatory cost of setting up a new business in 85 countries, and find a negative correlation between GDP per capita and the ratio of entry cost to GDP per capita. Nicoletti and Scarpetta (2003) and (2006) find that entry barrier is negatively related to TFP in OECD countries. Moreover, Lewis (2004) provides industry evidence that product market regulation negatively affects productivity in both rich and poor countries.

Motivated by these empirical works, this paper studies how entry barriers affect technology adoption. The model developed in this paper builds on the monopolistic competition framework with a final good sector and many intermediate goods industries. In each industry, there is an incumbent and a potential entrant. Both of these two firms make their technology choice based on adoption costs and compete with each other in Bertrand fashion. This industry structure is related to Aghion et. al (2006). However, Aghion et. al (2006) investigates how entry barriers affect the incumbent firm's technology choice in rich countries. To analyze the large differences in TFP between rich and poor countries, this paper deviates from Aghion et. al (2006) mainly in two ways. First, the available technology set

[1] See for example Klenow and Rodriguez-Clare (1997), Prescott (1998), Hall and Jones (1999). One exception is Manuelli and Seshadri (2005)

is continuous, and second, entrants do not operate at the technology frontier without cost. As a result, the model can generate the negative relationship between entry barriers and technology adoption, and countries with higher entry barriers are characterized by the use of less advanced technologies and lower TFP.

Four findings emerge from the model. The first one is that the lack of competition leads to adoption of less productive technologies. In particular, the paper demonstrates that the technology adopted in the economy with entry threats is at least as good as the technology adopted in the economy without entry threats. The second finding is that higher entry barriers lead to adoption of less productive technologies. The third finding is that the effect of entry barriers on technology adoption is characterized by threshold effects. In particular, if entry barriers are below the threshold, a small reduction in entry barriers leads to adoption of more productive technologies. However, if entry barriers are above the threshold, a small reduction in entry barriers has no effect on technology adoption. The fourth finding is that entry barriers could be an quantitatively important reason for the cross-country differences in TFP and the size of the quantitative effects depends on the demand elasticity. Moreover, the quantitative effects are bigger when the demand is price inelastic.[2]

The key economic mechanism underlying these results is that higher entry barriers effectively reduce entry threats and lower entry threats lead to adoption of less productive technologies. To understand this, it is useful to first consider an economy without the potential entrants. In this simpler economy, the incumbent's incentive of adopting better technologies is to reduce production costs. In the economy with potential entrants, the incumbent has more incentive to adopt better technologies, since if it adopts a low technology, the potential entrant will come in and steal the market. The lower the entry barriers are, the better the technology the incumbent has to adopt in order to prevent entry. However, when the entry

[2] Although these results are derived from the static model presented in this paper, I have shown in another paper that all of them still hold in a dynamic version of the model.

barriers are sufficiently large, the incumbent knows for sure that the potential entrant will not enter, and therefore adopts the same technology as that in the economy without potential entrants. It follows that entry barriers have no effects on technology adoption when they are sufficiently large, and have negative effects on technology adoption otherwise. The idea of entry deterrence in this paper relates to the industrial organization literature that investigates firm's strategic behavior. Examples include Fudenberg and Tirole (1984) and Bulow et. al (1995). However, a major focus of these papers has been on the industry level instead of the aggregate level.

This paper is related to the literature which examines firms' incentive of adopting new technologies.[3] It also relates to the literature which offers theory for the cross-country differences in TFP.[4] Among those, the most related ones are Parente and Prescott (1999) and Herrendorf and Teixeira (2007). These two papers also examine the effects of barriers to entry on TFP, but they study the entry barriers in the labor market and unions act as the barrier to the adoption of new technologies. In contrast, this paper studies the entry barriers in the product market and the regulatory costs of setting up a new business act as the barrier to the adoption of better technologies. The paper shows that entry barriers in the product market can also have negative consequences for technology adoption. In addition, because the entry barrier is modeled as a fixed entry cost to the product market, the model developed in this paper has the potential to be connected with the data on the entry cost constructed by Djankov et. al. (2002). Moreover, this paper has implication about the importance of demand elasticity on the quantitative effect of entry barriers on technology adoption. In particular, the paper shows that entry barriers are more harmful in countries with monopolist facing inelastic demand.

[3]Examples include Krusell and Rios-Rull (1996), Bellettini and Ottaviano (2005), Bridgman et. al (2007), Acemoglu (2007), Holmes et. al (2008), and Desmet and Parente (2008).

[4]Examples include Amaral and Quintin (2007), Erosa and Hidalgo (2008), Buera et. al (2008), Guner et al. (2006), Acemoglu and Robinson (2000), Acemoglu et al. (2002), Holmes and Schmitz (1995), Herrendorf and Teixeira (2005), and Easterly and Levine (2003).

The rest of the paper is organized as follows. Section 2 lays out the economic environment. Section 3 defines the symmetric equilibrium. Section 4 defines the limited competition economy and characterizes the symmetric equilibrium in this economy. Section 5 characterizes the symmetric equilibrium defined in section 3. Section 6 assesses the quantitative effects of entry barriers on technology adoption. Section 7 concludes.

2 Model

The model can be best described as a standard monopolistic competition model with technology adoption choice. As the standard model, there is a representative household, and two production sectors: a final good sector and an intermediate goods sector. The intermediate goods sector consists of a continuum of measure 1 of industries and each industry produces a distinct intermediate good. The new ingredient is that in each industry, there is an incumbent and a potential entrant and both of them can adopt new technologies from a continuous set of available technologies.

2.1 Household

There is a representative household with preferences defined over consumption of a single good c given by:

$$\frac{c^{1-\sigma}-1}{1-\sigma} \tag{2.1}$$

The parameter σ satisfies $\sigma \geq 0$. There is no labor-leisure choice. The representative household has a time endowment of one. The household owns all firms and hence will receive all profits.

2.2 Production

2.2.1 Final Good Production

There are two production sectors: an intermediate goods sector and a final good sector. The intermediate goods sector consists of a continuum of mass one of industries, each of which produces a distinct intermediate good. The final good is produced by a representative firm which combines intermediate goods into the final good via the production function:

$$y = \left(\int_0^1 x_j^{\frac{\epsilon - 1}{\epsilon}} d_j \right)^{\frac{\epsilon}{\epsilon - 1}} \tag{2.2}$$

For now, I assume that the demand for the intermediates is price inelastic, that is $0 < \epsilon < 1$. The case with $\epsilon > 1$ will be discussed later.[5]

2.2.2 Intermediate Goods Production

There is a continuum of measure one of industries, each of which produces a distinct intermediate x. For reasons of tractability, the environment is symmetric with respect to intermediates. Hence, I will not specify the industry index unless it is necessary.

In each industry, there is a continuum of technologies available, indexed by their labor productivity. In particular, each technology is of the form $x = Ah$, where h is the labor input, and $A \in [0, A^f]$. A^f is the technology frontier. In what follows, I will identify a technology by its value of A.

Each industry consists of one incumbent, one informal incumbent and one potential entrant. Each incumbent is endowed with an initial technology A_0 where $A_0 < A^f$. At the beginning of the period, the incumbent makes a choice about updating its technology. The cost of updating from A to A' is given by $\phi^i d(A, A')$, and is measured in units of the

[5] Although the qualitative implications are not dependent on whether ϵ is less than one or greater than one, the details of the arguments are different in the two cases, and therefore, they must be handled separately.

final good. The updating cost could differ across countries, and the differences are captured by the differences in the shift parameter ϕ^i. The function d is strictly decreasing in its first argument, strictly increasing and strictly convex in its second argument, and satisfies $d(A, A) = 0$ for all A.

Each informal incumbent can only operate with its endowed technology $\underline{A}$, where $\underline{A} < A_0$. The informal incumbent can be thought of as street vendors, which operate with very low technologies.

The potential entrant has to pay a cost κ to enter, where κ is the parameter that indexes the size of the barriers to entry in different countries, and is also measured in units of the final good. I assume that $\kappa \geq 0$. This implies that subsidies on entry are excluded. Conditional on paying κ, the potential entrant then chooses a technology $A \in [\underline{A}, A^f]$ and incurs a cost of $\phi^e d(\underline{A}, A)$, where d is the same function introduced earlier.[6] This implies that $d(\underline{A}, \underline{A}) = 0$. Comparing with the informal incumbent, the potential entrant can also use $\underline{A}$ for free, but paying κ gives the potential entrant a right to adopt a technology better than $\underline{A}$.[7] ϕ^i and ϕ^e could be different and the difference reflects the difference in the adoption cost of the incumbent and the potential entrant. For example, if the new technology needs a lot of reorganization, the potential entrant will have a lower adoption cost and $\phi^e < \phi^i$. But if experience is crucial in adopting the new technology, the incumbent will have a lower adoption cost and $\phi^i < \phi^e$.

2.3 Timing

In a given industry, the players are the incumbent, the informal incumbent and the potential entrant. They play a four-stage game. In the first stage, the incumbent chooses which

[6]The parameter ϕ^e is again a shift parameter that could vary across countries.

[7]The first argument in the adoption cost function for the potential entrant represents an obsolete technology that has a zero adoption cost. All the results in this paper will not change if this technology is different from $\underline{A}$.

technology to upgrade to. In the second stage, the potential entrant decides whether to enter, and if so, its level of technology. If the potential entrant does not enter, then in the third stage, the incumbent and the informal incumbent play a Bertrand game. If the potential entrant does enter, then, the potential entrant, the informal incumbent and the incumbent play a Bertrand game in the third stage. In the fourth stage, production and consumption take place and the game ends.

3 Equilibrium

This section defines the decentralized equilibrium for the economy just described. The equilibrium concept is symmetric sub-game perfect where all incumbents behave identically, all informal incumbent behave identically and all potential entrants behave identically. This equilibrium has the following features. The consumer behaves competitively in both the final output and the labor market, and the final good producer behaves competitively in both the final good market and the intermediate goods market. Intermediate goods producers behave competitively in the labor market and play the four-stage game described earlier in the intermediate goods market. Since each industry is small, players in each industry play the four-stage game taking as given the demand for the output of their industry, the wage in the competitive labor market and the price of the final good.

In what follows, I denote the wage rate by w and the price of intermediate goods by p. The price of the final good is normalized to 1. Since the equilibrium is sub-game perfect, it is solved by backward induction.

3.1 Household Sector

The household sector is standard. Taking prices and profits as given, the household maximizes utility subject to its budget constraint:

$$\max_{c} \frac{c^{1-\sigma}-1}{1-\sigma}$$
$$s.t. \quad c = w + \pi,$$

where π is the total profits.

3.2 Final Good Sector

The final good producer maximizes profit taking as given the prices of inputs $(p_j)_{j=0}^{1}$ and the price of the final good which is normalized to 1.

$$\max_{x_j} \left(\int_0^1 x_j^{\frac{\epsilon-1}{\epsilon}} d_j \right)^{\frac{\epsilon}{\epsilon-1}} - \int_0^1 p_j x_j d_j$$

The solution to this problem gives the individual demand function for each intermediate j:

$$x_j = B p_j^{-\epsilon}, \tag{3.1}$$

where $B = \left(\int_0^1 x_j^{\frac{\epsilon-1}{\epsilon}} d_j \right)^{\frac{\epsilon}{\epsilon-1}}$.

3.2.1 Intermediate Goods Sector

In each industry, the incumbent, the informal incumbent and the potential entrant play the game described earlier, taking as given the demand for their product, the wage w and the price of the final good.

Stage 3: In stage 3, the incumbent's technology A^i, and the potential entrant's entry decision and technology A^e have all been determined. If there is no entry in stage 2, the incumbent and the informal incumbent play a two firm Bertrand game. In a two firm Bertrand game, the firm with lower marginal cost will capture the entire market and charge a price which is no greater than the higher marginal cost. Since $A_0 > \underline{A}$, the incumbent necessarily has a better technology than the informal incumbent, and therefore charges a price no greater than the informal incumbent's marginal cost $\frac{w}{\underline{A}}$ and solves the following problem:

$$\begin{aligned} & \max_p Bp^{-\epsilon}(p - \frac{w}{A^i}) \\ s.t. \qquad & p \leq \frac{w}{\underline{A}} \end{aligned}$$

The fact that the demand is inelastic implies that the incumbent wants to charge a price as high as possible, or equivalently, produce as little as possible, hence,

$$p = \frac{w}{\underline{A}} \tag{3.2}$$

If, instead, the potential entrant has entered, the incumbent, the informal incumbent and the potential entrant play a three firm Bertrand Game.[8] Similar to the two firm Bertrand game, in a three firm Bertrand game, the firm with the lowest marginal cost will capture the entire market and charge a price which is no greater than the second lowest marginal cost. If the potential entrant does enter, it must have a better technology than the incumbent and the informal incumbent, since otherwise, the potential entrant cannot make any profit in stage 3 to cover the entry cost in stage 2, and therefore, would never have entered. Since the incumbent has a better technology than the informal incumbent, conditional upon entry, the potential entrant charges a price no greater than the incumbent's marginal cost $\frac{w}{A^i}$ and

[8]If the incumbent and the potential entrant have the same technology, I assume that the incumbent will capture all the market demand.

solves the following problem in stage 3:

$$\max_{p} Bp^{-\epsilon}(p - \frac{w}{A^e})$$
$$s.t. \qquad p \leq \frac{w}{A^i}$$

Since the demand is price inelastic, the price constraint again holds with equality, i.e.,

$$p = \frac{w}{A^i} \tag{3.3}$$

Stage 2: In the second stage, the potential entrant makes its entry decision. If the profit the potential entrant can make after entry is higher than the entry cost, the potential entrant will enter, otherwise, it will not enter. Conditional upon entry, the potential entrant maximizes profit taking as given the demand function, the wage w, the price of the final good and the incumbent's technology A^i. Therefore, the potential entrant's problem in stage 2 is:

$$\max_{A^e,p}[Bp^{-\epsilon}(p - \frac{w}{A^e}) - \phi^e d(\underline{A}, A^e)]$$
$$s.t. \qquad p = \frac{w}{A^i}$$
$$\underline{A} \leq A^e \leq A^f$$

It is easy to show that this maximization problem is strictly concave, and therefore has a unique solution. Let $\pi^e(A^i, B, w)$ be the value of this maximization problem. The potential entrant makes the entry decision by comparing $\pi^e(A^i, B, w)$ and κ. If $\pi^e(A^i, B, w) \leq \kappa$, the potential entrant will not enter, and if $\pi^e(A^i, B, w) > \kappa$, the potential entrant will enter. For future reference, it is easy to show that π^e is decreasing in A^i. To see this, note that the price p the potential entrant charges is $\frac{w}{A^i}$ and inelastic demand implies that $\pi^e(A^i, B, w)$ is increasing p, hence decreasing in A^i.

Stage 1 : Because $\pi^e(A^i, B, w)$ is decreasing in A^i, the incumbent can alter its choice of A^i to influence the potential entrant's entry decision. In particular, in order to end up with positive profit, the incumbent must choose A^i, s.t $\pi^e(A^i, B, w) - \kappa \leq 0$. Otherwise the potential entrant will enter and the incumbent will have zero sales. Let π^B be the incumbent's maximum profit when it chooses A^i so as to prevent entry. Then, π^B is given by:

$$\begin{aligned}
\pi^B &= \max_{A^i, p} Bp^{-\epsilon}(p - \frac{w}{A^i}) - \phi^i d(A_0, A^i) \\
s.t. \quad & \pi^e(A^i, B, w) - \kappa \leq 0 \\
& p = \frac{w}{\underline{A}} \\
& A_0 \leq A^i \leq A^f
\end{aligned}$$

If $\pi^B \geq 0$, then it is optimal for the incumbent to update its technology, in which case, the potential entrant does not enter, and I will say entry is "blocked".[9] Otherwise, it is not profitable for the incumbent to update its technology, in which case, the incumbent have zero sales and the potential entrant enters, and I will say entry is not "blocked".

Definition 1: (Symmetric Equilibrium) A symmetric, sub-game perfect equilibrium is a set of prices (w, p, p^e, p^i), allocations (c, x), technologies (A^i, A^e) and entry decision E such that:

(i) E solves the representative entrant's entry problem. In particular, $E = 1$ reflects entry and $E = 0$ reflects no entry;

(ii) When $E = 0$, (A^i, p^i) solves the incumbent's problem, and $p = p^i$;

(iii) When $E = 1$, (A^e, p^e) solves the entrant's problem, and $p = p^e$.

(iv) c solves the representative consumer's problem;

(v) x solves the final good producer's problem;

(vi) Markets clear.

[9] It could also be the case that entry is blocked even if the incumbent does not update its technology.

There are two types of symmetric equilibria: equilibrium with entry and equilibrium without entry. From now on, I refer to them as the symmetric equilibrium without entry, and the symmetric equilibrium with entry.

4 The Limited Competition Economy

To understand the results that follow it is useful to first consider a simpler economy which is the economy just described except without potential entrants. This economy will serve as a useful benchmark. In this economy, the incumbent only faces competition in their own market from the informal incumbent. Moreover, because the informal incumbent can only use an inferior technology, this competition is rather limited. For this reason, I will refer to this as the limited competition economy.

In the limited competition economy, the incumbent solves the following problem:

$$\begin{aligned} &\max_{A,p} Bp^{-\epsilon}(p - \frac{w}{A}) - \phi^i d(A_0, A) \\ s.t. \quad &p \leq \frac{w}{\underline{A}} \\ &A_0 \leq A \leq A^f \end{aligned}$$

As noted earlier, the incumbent will necessarily set $p = \frac{w}{\underline{A}}$. It is easy to show that the incumbent's objective function is strictly concave in A for given values of B and w, hence, if the solution is interior, it is unique and determined by the first order condition.

Substituting $p = \frac{w}{\underline{A}}$ into the incumbent's first order condition for A yields:

$$\frac{B\underline{A}^{\epsilon} w^{1-\epsilon}}{(A)^2} - \phi^i \frac{\partial d(A_0, A)}{\partial A} = 0 \tag{4.1}$$

In a symmetric equilibrium, $x_j = A$ for all j. This implies that $B = A$. Substituting $x_j = A$ for all j, $B = A$ and $p = \frac{w}{\underline{A}}$ into the final good producer's first order condition gives $w = \underline{A}$.

Substituting $w = \underline{A}$ and $B = A$ into (4.1) yields:

$$1 - \frac{A}{\underline{A}}\phi^i \frac{\partial d(A_0, A)}{\partial A} = 0 \tag{4.2}$$

Let A^{LC} be the incumbent's technology in the symmetric equilibrium of the limited competition economy. Since d is strictly convex in A, the left of (4.2) is strictly decreasing in A, and crosses zero at most once. It follows that if A^{LC} is interior, it is unique and determined by (4.2), otherwise, it is either A_0 or A^f. The incumbent's profit can then by derived, which is $A^{LC} - \underline{A} - \phi^i d(A_0, A^{LC})$. For the existence of the symmetric equilibrium in the limited competition economy, this profit must be nonnegative. In what follows, I assume that this is always true.

If $A^{LC} = A^f$, then, the economy with limited competition will adopt the frontier technology. Since my focus is on how the lack of competition can retard technology adoption, this case is of limited interest, and in what follows, I will assume that $A^{LC} < A^f$.

For future reference, note that when the entry cost is infinite in the economy with potential entrants, the incumbent knows for sure that the potential entrant will not enter, and can behave as if there are no potential entrants, hence the economy with infinite entry cost has the same equilibrium as the limited competition economy.

5 Symmetric Equilibrium

This section analyze the symmetric equilibrium defined earlier. The first part of this section focuses on the symmetric equilibrium without entry, and the second part focuses on the symmetric equilibrium with entry.

5.1 Symmetric Equilibrium Without Entry

5.1.1 Existence and Uniqueness

This section establishes the existence and uniqueness of the symmetric equilibrium without entry as a function of the parameters ϕ^i, ϕ^e and κ. In general, one would not expect such an equilibrium to exist for all combinations of these three parameters. For example, if ϕ^i is infinity, and ϕ_e and κ are both 0, the potential entrants will enter for sure and a symmetric equilibrium without entry cannot exist. However it is easy to show that such an equilibrium does exist for a large set of ϕ^i, ϕ^e and κ. In particular, it is intuitive that such an equilibrium will exist for a given ϕ^i if ϕ^e and κ are sufficiently large. To see this, note that given ϕ^i and κ, if ϕ^e is sufficiently large, the potential entrant needs to pay a higher cost to adopt any technology, making it easier for the incumbent to block entry. Similarly, given ϕ^i and ϕ^e, if κ is sufficiently big, the potential entrant needs to pay a higher cost to overcome entry, also making it easier for the incumbent to block entry. This analysis is formalized in Proposition 1.

Proposition 1: Holding ϕ^i constant, if ϕ^e and κ are sufficiently large,[10] the symmetric equilibrium without entry exists and is unique.

Proof: See Appendix.

To guarantee existence, it is not necessary to have both κ and ϕ^e to be large. In fact, as long as one of them is large enough, the symmetric equilibrium without entry exists. For example, for a given ϕ^i and $\phi^e = \infty$, the symmetric equilibrium without entry exists even when $\kappa = 0$. Similarly, for a given ϕ^i and $\kappa = \infty$, the symmetric equilibrium without entry exists even when $\phi^e = 0$. This implies that the set of κ that guarantees existence depends on the value of ϕ^i and ϕ^e, and the set of ϕ^e that guarantees existence depends on the value of ϕ^i and κ. In particular, the proof of Proposition 1 shows that for a given pair of ϕ^i and ϕ^e,

[10] Please see the cutoff value of ϕ^e and κ in the proof of Proposition 1.

there exists a κ_C such that when κ is greater than κ_C[11], the symmetric equilibrium without entry exists.

Although it is easy to establish existence, it takes some work to establish uniqueness. The issue comes from the strategic complementarity between the technology choices of the incumbents. To see it, note that the potential entrant $j's$ profit $\pi^e_j(A^i_j, B, w)$ is decreasing in the incumbent $j's$ technology A^i_j, and increasing in B, where $B = \left(\int_0^1 x_j^{\frac{\epsilon-1}{\epsilon}} d_j\right)^{\frac{\epsilon}{\epsilon-1}}$ is the constant in the demand function. Let A^i_{-j} be the technology adopted by the incumbents in all of the other industries. It follows that $\pi^e_j(A^i_j, B, w)$ is also increasing in A^i_{-j}, since the incumbent $j's$ demand $Bp_j^{-\epsilon}$ is increasing in A^i_{-j}. More importantly, holding A^i_{-j} constant, in an symmetric equilibrium without entry, the incumbent j will upgrade to a technology which equalizes the potential entrant $j's$ profit and the entry cost. Hence as A^i_{-j} increases, it takes a higher A for the incumbent j to block entry. In other words, if everyone else has adopted a higher A then it is also necessary for the incumbent j to adopt a higher A. This implies that the technology adoption choices among incumbents are strategic complements. Cooper and John (1998) then suggests the possibility of multiple symmetric equilibria without entry. However, if A^i_j is not very responsive to the change in A^i_{-j}, the strategic effects will not be sufficiently strong to produce multiple equilibria. This is guaranteed by large enough ϕ^e.[12] The idea behind this is intuitive. Increases in ϕ^e make it more costly for the potential entrant to adopt a better technology. This retards the response of the potential entrant $j's$ choice of technology to the changes in A^i_{-j}, and therefore, retards the response of the incumbent $j's$ choice of technology to the changes in A^i_{-j}. Hence, if ϕ^e is sufficiently large, A^i_j is not very responsive to the change in A^i_{-j}, and the symmetric equilibrium without entry is unique. In what follows, I will assume that existence and uniqueness hold.

Corollary 1: If $\phi^e \geq \phi^i$, there exists a symmetric equilibrium without entry for any

[11]Please refer to the proof of Proposition 1 for the expression of κ_C.

[12]it is not necessary to have $\phi^e > \phi^i$ to guarantee the uniqueness. In fact, even when $\phi^i = \phi^e$, the symmetric equilibrium without entry is unique in all the examples provided in section 6.

$\kappa \geq 0$, and there does not exist a symmetric equilibrium with entry for any $\kappa \geq 0$.

Proof: See Appendix.

To understand Corollary 1, note that when $\phi^e \geq \phi^i$, the incumbent can always make greater profit than the potential entrant. Because the potential entrant faces a higher adoption cost for any technology and also needs to pay the entry cost, Hence, a symmetric equilibrium with entry cannot exist, and in contrast, a symmetric equilibrium without entry exists.

5.1.2 Characterizing the Symmetric Equilibrium Without Entry

This subsection analyzes some properties of the symmetric equilibrium without entry. Let A^{NE} be the technology adopted by the incumbent in the symmetric equilibrium without entry. The following proposition summarizes several properties of A^{NE} holding ϕ^i and ϕ^e constant.

Proposition 2: There exists κ_{LC}[13], s.t if $\kappa \geq \kappa_{LC}$, $A^{NE} = A^{LC}$, and if $\kappa_C \leq \kappa < \kappa_{LC}$, $A^{NE} > A^{LC}$.

Proof: See Appendix.

Proposition 2 describes the effects of entry barriers on the technology adopted in the symmetric equilibrium without entry. κ_{LC} in this Proposition is the level of entry barriers such that when the incumbent adopts A^{LC}, the potential entrant is indifferent between to enter and not to enter. As noted in section 4, if the entry cost is infinite, the incumbent does not need to worry about the existence of the potential entrant, and therefore will upgrade to A^{LC}. By continuity, this is true for sufficiently large entry costs, and κ_{LC} is the cutoff value. However, if the entry cost is sufficiently low, the incumbent has to upgrade to a technology better than A^{LC} in order to block entry, since otherwise, the potential entrant will enter and steal the market. This implies that even if there is no entry, the entry threat can still lead

[13] Please refer to the proof Lemma 1 in the appendix for the expression of κ_{LC}.

to a better technology in the economy,

In the limited competition economy, the incumbent experiences relatively little competition since the informal incumbent's technology is low and fixed. But, when there are potential entrants, competition becomes intense. Proposition 2 has proved that the technology in the economy with potential entrants is at least as good as that in the economy without potential entrants. This reflects one of the key features of the model: the lack of competition leads to adoption of less productive technologies.

The next proposition summarizes the comparative statics of the parameters ϕ^i, ϕ^e and κ on technology adopted in the symmetric equilibrium without entry.

Proposition 3: (Comparative Statics) If $\kappa \geq \kappa_{LC}$, A^{NE} is decreasing in ϕ^i, and does not depend on κ and ϕ^e. If $\kappa_C \leq \kappa < \kappa_{LC}$, A^{NE} is decreasing in ϕ^e and κ, and does not depend on ϕ^i.

Proof: See Appendix.

The intuition behind proposition 3 is straightforward. To begin with, note that when $\kappa \geq \kappa_{LC}$, $A^{NE} = A^{LC}$, in which case κ and ϕ^e are irrelevant for the choice of technology. However, larger ϕ^i does decrease A^{NE}, since larger ϕ^e implies higher adoption costs. When $\kappa_C \leq \kappa < \kappa_{LC}$, as ϕ^e increases, the potential entrant's profit decreases, hence, the incumbent can block entry by upgrading to a less productive technology. Similarly, as κ increases, the potential entrant's net profit of entry decreases, hence the incumbent can also block entry by upgrading to a less productive technology.

It may seem puzzling that ϕ^i has such different effects on the technology adopted when κ is in different ranges. However, the intuition behind this result is simple. To see it, note that when making the choice of technology, the incumbent considers both the size of the adoption cost and the threat of entry. When $\kappa \geq \kappa_{LC}$, the incumbent does not need to worry about the entry threat, hence it chooses the technology solely depending upon the size of the adoption cost. But when $0 \leq \kappa < \kappa_{LC}$, the incumbent must take into account the fact that the potential entrant may enter, and hence, upgrades to a larger A, thereby incurring a higher cost. In particular, to maximize profit, the incumbent upgrades to the lowest possible technology to block entry, which is the technology that gives the potential entrant zero value of entry. This technology is solely determined by the potential entrant's maximization problem, and therefore does not depend on ϕ^i.

Proposition 3 implies that the relation between entry barriers and technology adoption is characterized by threshold effects. This follows from the fact that A^{NE} does not depend on κ when $\kappa \geq \kappa_{LC}$ and is decreasing in κ when $\kappa_C \leq \kappa \leq \kappa_{LC}$. This finding has implications for empirical studies, since they often impose a linear relationship. This finding also has policy implications. In countries with entry barriers below the threshold κ_{LC}, a small reduction in entry barriers leads to adoption of more productive technologies. But in countries with entry barriers above the threshold, a small reduction in the entry barriers has no effect on technology adoption. Observing such an outcome, one might be tempted to conclude that reducing barriers is not beneficial for technology adoption. But in fact, the correct conclusion may simply be that entry barriers have not been reduced enough.

5.1.3 Welfare in the Symmetric Equilibrium without Entry

It is also of interest to examine the effects of the entry cost κ on welfare. In this static economy, consumption is one appropriate measure of welfare. When $\kappa \geq \kappa_{LC}$, consumption equals $A^{LC} - \phi^i d(A_0, A^{LC})$ in the symmetric equilibrium without entry, and does not change with the entry cost.

When $\kappa_C \leq \kappa < \kappa_{LC}$, consumption c equals $A^{NE} - \phi^i d(A_0, A^{NE})$. From Proposition 3, A^{NE} is decreasing in κ. It follows that consumption is decreasing in κ if c is increasing in A^{NE}, and is increasing in κ if c is decreasing in A^{NE}. The derivative of c with respect to A^{NE} is:

$$\frac{\partial c}{\partial A^{NE}} = 1 - \phi^i \frac{\partial d(A_0, A^{NE})}{\partial A^{NE}} \tag{5.1}$$

Since d is strictly convex in A^{NE}, $\frac{\partial c}{\partial A^{NE}}$ is strictly decreasing in A^{NE}. Let κ_W be the value of κ which induces the A^{NE} such that $\frac{\partial c}{\partial A^{NE}} = 0$. $\frac{\partial A^{NE}}{\partial \kappa} < 0$ and $\frac{\partial^2 c}{\partial (A^{NE})^2} < 0$ then imply $\frac{\partial c}{\partial A^{NE}} > 0$ if $\kappa > \kappa_W$, and $\frac{\partial c}{\partial A^{NE}} < 0$ if $\kappa < \kappa_W$. Comparing (4.2) and (5.1), it is easy to see that $\frac{\partial c}{\partial A^{NE}}|_{A^{NE}=A^{LC}} > 0$, hence, κ_W is smaller than κ_{LC}. If κ_W is also smaller than κ_C, consumption is always increasing in A^{NE}, and therefore is always decreasing in κ in the symmetric equilibrium without entry. In this case, reducing barriers to entry increases welfare, since more productive technologies are used.

However, if $\kappa_W > \kappa_C$, consumption is increasing in A^{NE} when $\kappa \in [\kappa_W, \kappa_{LC}]$, and is decreasing in A^{NE} when $\kappa \in [\kappa_C, \kappa_W)$. Hence, consumption is decreasing in κ when $\kappa \in [\kappa_W, \kappa_{LC}]$, and is increasing in κ when $\kappa \in [\kappa_C, \kappa_W)$. The intuition behind this is simple. When $\kappa \in [\kappa_W, \kappa_{LC}]$, as κ decreases, the incumbent adopts a better technology, hence output increases and consumption increases. But, when $\kappa \in [\kappa_C, \kappa_W)$, the entry cost is so low that as κ decreases, to block entry, the incumbent has to adopt a technology so costly that the increase in output by using this technology is smaller than the increase in the cost of adopting this technology, hence consumption decreases. Note that cost to technology adoption can be viewed as investment in the current model, and therefore this result can also be interpreted as when $\kappa \in [\kappa_C, \kappa_W)$, to compete with its rival, the incumbent has to overinvest.

In the context of this model, taking all costs as given, social planner will always choose a technology to maximize consumption. The above results then imply that the equilibrium technology could be either less than the socially optimal level, or greater than or equal to the socially optimal level.[14] This happens because the incumbent's objective, blocking entry so as to maximize profit, is different from the social planner. In particular, when the entry cost is small enough, the incumbent even over upgrades to block entry.

[14]This has the same spirit as Mankiw and Whinston (1986), which demonstrates that when there are fixed set-up costs upon entry, imperfect competition and business-stealing effect, the number of firms in a free-entry equilibrium could be greater than, less than or equal to the socially optimal level.

5.2 Symmetric Equilibrium With Entry

The symmetric equilibrium without entry exists if ϕ^e and κ are sufficiently large. In contrast, a symmetric equilibrium with entry exists if ϕ^e and κ are small. For example, if ϕ_e and κ are both 0, the potential entrant will enter and a symmetric equilibrium with entry does exist. In fact, Proposition 4 proves that when ϕ^e and κ are sufficiently small, the symmetric equilibrium with entry exists and is unique. Because as ϕ^e or κ becomes smaller, it is more profitable for the potential entrant to enter, or equivalently, less profitable for the incumbent to block entry. The uniqueness of this equilibrium is guaranteed by the convexity of the cost functions.

Proposition 4: Holding ϕ^i constant, If ϕ_e and κ are sufficiently small, the symmetric equilibrium with entry exists and is unique.

Proof: See appendix.

In the symmetric equilibrium with entry, it is not profitable for the incumbent to block entry, and therefore, the incumbent does not update its technology and does not produce. Let A^E be the technology adopted by the potential entrants in the symmetric equilibrium with entry. Proposition 5 summarizes the comparative static in this equilibrium.

Proposition 5: A^E is decreasing in ϕ^e, and does not depend on κ and ϕ^i.

Proof: See Appendix.

The intuition behind Proposition 5 is simple. Bigger ϕ^e increases the potential entrant's adoption cost, hence leads to adoption of less productive technology. Conditional on entry, the entry cost is treated as sunk cost by the potential entrant, this is why it has no effect on the potential entrant's choice of technology. Once the incumbent's monopoly power is broken, ϕ^i is irrelevant, hence it does not affect A^E. In the symmetric equilibrium with entry, consumption equals $A^E - \phi^e d(\underline{A}, A^E) - \kappa$. Since A^E does not depend on κ, it is obvious that welfare is decreasing in κ. This is because more resources are used to overcome the barriers to entry.

Since the existence of the symmetric equilibria depends on the size of the entry barriers, a natural question to ask is whether the type of equilibrium switches when the entry cost changes while all the other parameters are constant. It turns out that by choosing different pair of ϕ^i and ϕ^e, varying κ can produce three cases. In the first case, only the symmetric equilibrium without entry exists. This happens when ϕ^e is large enough relative to ϕ^i. In particular, Corollary 1 proves that as long as $\phi_e \geq \phi^i$, the symmetric equilibrium with entry does not exist and the symmetric equilibrium without entry exists for any κ.

In the second case, the symmetric equilibrium switches from one to another while κ varies, but there is a range of κ in which no symmetric equilibrium exists. In the third case, not only the symmetric equilibrium switches, but also they can exist at the same time in some range of κ. This happens because of the general equilibrium effects in the model. To see it, recall that the price the potential entrant charges is the ratio between the wage rate and the incumbent's technology, and it is easy to derive that the wage rate is $\underline{A}$ in the symmetric equilibrium without entry and is A_0 in the symmetric equilibrium with entry. It follows that if there is entry in all the other industries, the potential entrant j can charge a price of $p_j^e = \frac{w}{A_j^i} = \frac{A_0}{A_j^i}$, and if entry can be blocked in all the other industries, the potential entrant j can charge a price of $p_j^e = \frac{w}{A_j^i} = \frac{\underline{A}}{A_j^i}$. Hence, for any A_j^i, the potential entrant j can charge a higher price if there is entry in all the other industries, and therefore makes higher profits in this case. This implies that when there is entry in all the other industries, it is more profitable for the potential entrant j to enter as well. Similarly, when entry can be blocked in all the other industries, it is also more profitable for the incumbent j to block entry. This complementarity between the potential entrants as well as the complementarity between the incumbents may produces the coexistence of the symmetric equilibrium with entry and the symmetric equilibrium without entry for some combinations of ϕ^i and ϕ^e.

6 Numerical Examples

Two natural questions emerge from the analysis in section 5. One is how large is the quantitative effects of entry barriers on technology adoption, and the other one is how the primitives in the model affect the quantitative effects. To explore those two questions, I perform several numerical experiments in this section.

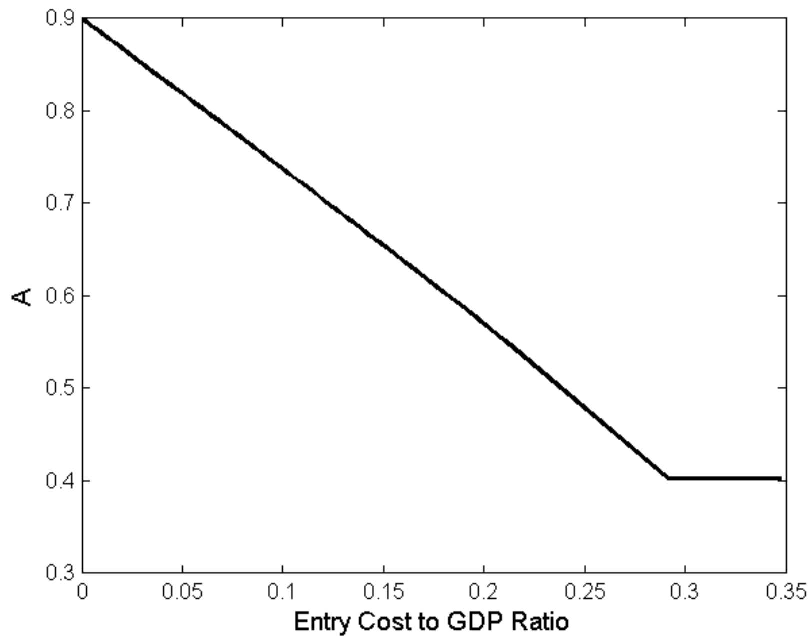
6.1 Quantitative Effects of Entry Barriers on Technology Adoption

To do the experiments, functional forms and parameter values need to be specified. I normalize the technology frontier A^f to 1. Following Parente and Prescott (1994), I pick $d(A, A') = \frac{(A')^{\gamma} - A^{\gamma}}{\gamma (A^f)^{\gamma - 1}}$. This cost function is derived from $d(A, A') = \int_A^{A'} (\frac{s}{A^f})^{\gamma - 1} ds$, which implies that it takes few resources to update from A to A' as the technology frontier increases. As a benchmark, I set $\gamma = 2$, $A_0 = 20\% A^f$, and $\underline{A} = 10\% A_0$. Following Parente and Prescott (1999), ϵ is set to be 0.9. The sensitivity test on these parameters are performed later. I set $\phi^i = \phi^e$ and then calibrate this value so that when the entry cost κ is 0, the technology adopted is 90% of the frontier technology. Note that from Corollary 1, when $\phi^i = \phi^e$, the symmetric equilibrium with entry does not exist and the symmetric equilibrium without entry exists for all $\kappa \geq 0$. Hence, κ_C is equal to 0 in all the experiments performed in this section.[15]

Figure 1 illustrates how the technology adopted changes with the entry cost to GDP ratio in the benchmark experiment. Based on figure 1, the relationship of entry cost and technology adopted described in Proposition 2 and Proposition 3 also holds when replacing the entry cost by entry cost to GDP ratio. In particular, when the entry cost to GDP ratio is bigger than 0.29, the technology adopted by the incumbent does not change with entry cost,

[15] The symmetric equilibrium without entry is unique for all the experiments performed in this section.

Figure 1: Benchmark Experiment



and when the entry cost to GDP ratio is smaller than 0.29, the technology adopted by the incumbent is decreasing in the entry cost. In this example, $\kappa_W = 0$, implying that welfare is always decreasing in the entry cost. Figure 1 also illustrates the size of the quantitative effects of entry barriers on TFP. Based on the figure, if the relative entry cost is reduced by 6 times from the threshold, TFP will increase by 2 times. Panel A of table III in Djankov et. al (2002) shows that the entry cost varies from 1.7% of GDP per capita in the U.S to 5 times of GDP per capita in Dominican Republic, and 6 times of difference in the entry cost to GDP ratio is not large at all. For example, the entry cost to GDP ratio is about 15 times larger in Argentina and is about 50 times larger in India than that in the U.S.

6.2 The Effects of the Primitives

This section explores how the primitives in the model affect the size of the quantitative effects of entry barriers on the technology adopted. To begin with, A_0 has little impact on the quantitative effects. To see this, note that when $\kappa_C \leq \kappa < \kappa_{LC}$, A_0 does not affect the equilibrium technology A^{NE}, since A_0 only affects the incumbent's adoption cost, and A^{NE} does not depend on the incumbent's adoption cost.[16] When $\kappa \geq \kappa_{LC}$, A_0 may affect A^{NE}, which equals A^{LC} in this case. However, the function d used in this section implies that the marginal cost of upgrading does not depend on A_0, hence A_0 does not affect A^{LC} as long as A^{LC} is interior, which is true for all the examples in this section.

I now turn to analyze how the demand elasticity ϵ affects the quantitative effects of entry barriers on technology adoption. Thus far the analysis has assumed that $0 < \epsilon < 1$, i.e., the demand for intermediates is price inelastic. In fact, under some reasonable conditions, the theoretical findings in section 5 also hold when the demand is price elastic. Hence, the numerical experiments here will cover both the elastic case and the inelastic case. In particular, I perform the following experiments. I set values for A_0, $\underline{A}$ and γ to be the same values as those in the benchmark experiment. I then choose different values for ϵ, and for each ϵ, I set $\phi^i = \phi^e$ and recalibrate them so that when $\kappa = 0$, the technology adopted is 90% of the frontier technology.

Figure 2 illustrates the results from the experiments on ϵ. Panel (a) shows the cases when $0 < \epsilon < 1$, while panel (b) shows the cases when $\epsilon > 1$. Three patterns emerge from figure 2. First, the size of the quantitative effects is smaller when the demand is price elastic. The intuition behind this is simple. The incumbent faces two types of competition. One is from the potential entrant in the same industry and the other is from the producers in other industries. If the intermediates are good substitutes, the incumbent faces intense competition from the producers in other industries, and therefore will adopt a better technology even when the entry barriers are high. As a result, the effects of entry barriers on technology adoption is much smaller when the demand is price elastic. This implies that entry barriers are more harmful in countries with monopolists facing inelastic demand.

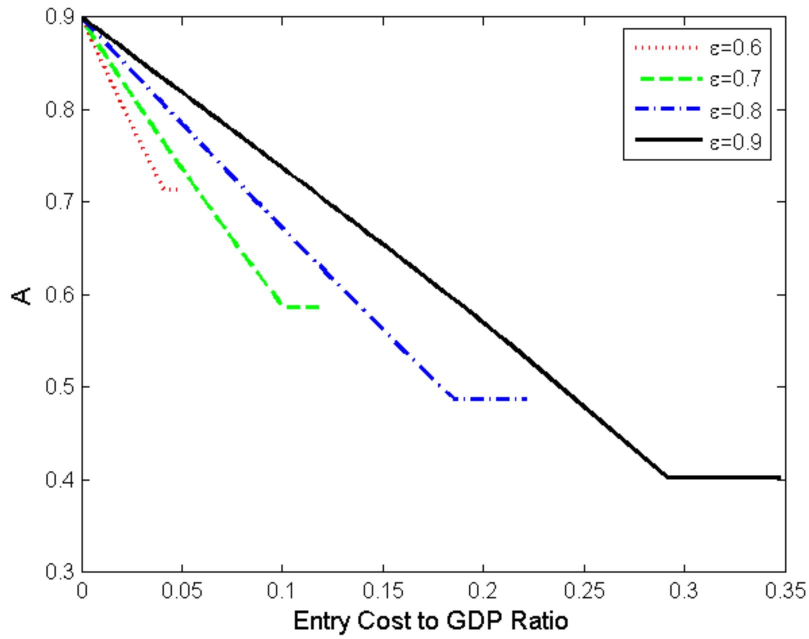
[16] This is similar to the argument that ϕ^i does not affect A^{NE} when $\kappa_C \leq \kappa < \kappa_{LC}$.

From panel (b) of figure 2, when the demand is price elastic, an increase in ϵ leads to an increase in A_{LC} and a decrease in κ_{LC}. Although only two curves are shown in figure 2(b), it turns out that when ϵ is greater than 1.5, $\kappa_{LC} = 0$ and $A_{LC} = 0.9$. The intuition behind this pattern is similar to the intuition behind the first pattern. As ϵ increases, competition among incumbents becomes more intense, hence, A^{LC} increases. The increase in A^{LC} then leads to the decrease in κ_{LC}, since as A^{LC} increases, the incumbent can block entry by adopting A^{LC} even if entry barrier is slightly lower. To see this, recall that κ_{LC} is the level of entry barriers such that when the incumbent adopts A^{LC}, the potential entrant is indifferent between to enter and not to enter.

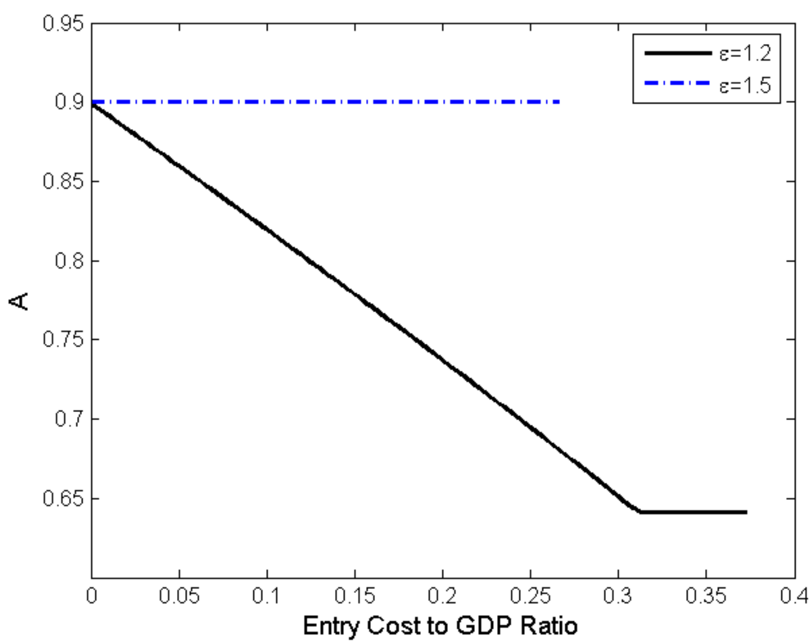
The third pattern is that when the demand is inelastic, as ϵ increases, A^{LC} decreases, κ_{LC} increases, and A^{NE} increases for any given entry cost when $0 \leq \kappa < \kappa_{LC}$. The intuition behind this is provided as follows. To begin with, when ϵ increases, ϕ^i increases, and therefore A^{LC} decreases. Although the decrease in A^{LC} is one reason for the increase in κ_{LC}, it is not the main reason. In fact, the main reason is that increases in ϵ lead to increases in the potential entrant's profit after entry. To see this, recall that the potential entrant must charge a price less than what the incumbent charges if it were to enter. As ϵ increases, the demand becomes more elastic, which implies that when the potential entrant undercut the incumbent's price, the demand responds more to this reduction in price, and therefore the potential entrant's revenue increases, or equivalently, the potential entrant's profit increases. It follows that κ_{LC} needs to be larger so that when $\kappa \geq \kappa_{LC}$, the incumbent can block entry by adopting A^{LC}. Moreover, when $0 \leq \kappa < \kappa_{LC}$, as ϵ increases, the incumbent has to adopt a higher A to block entry at any κ, since the potential entrant's profit is increasing in ϵ and decreasing in the incumbent's technology.

Figure 3 illustrates how $\underline{A}$ affects the quantitative effects of entry barriers on technology adoption. Similar to the experiments on ϵ, as $\underline{A}$ changes, I recalibrate ϕ^i and ϕ^e so that when $\kappa = 0$, the technology adopted is 90% of the frontier technology.

Figure 2: Effects of ϵ



(a) *Inelastic*



(b) *Elastic*

Figure 3: Effects of $\underline{A}$

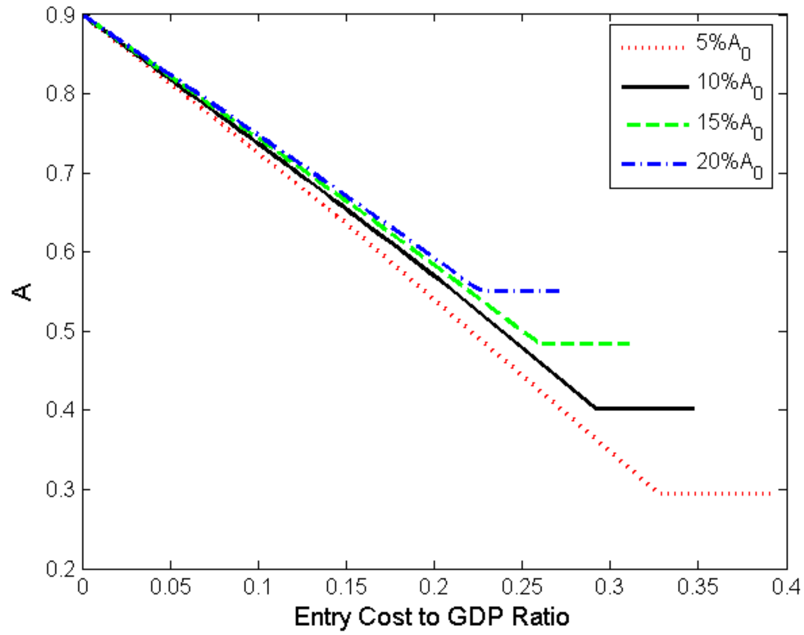
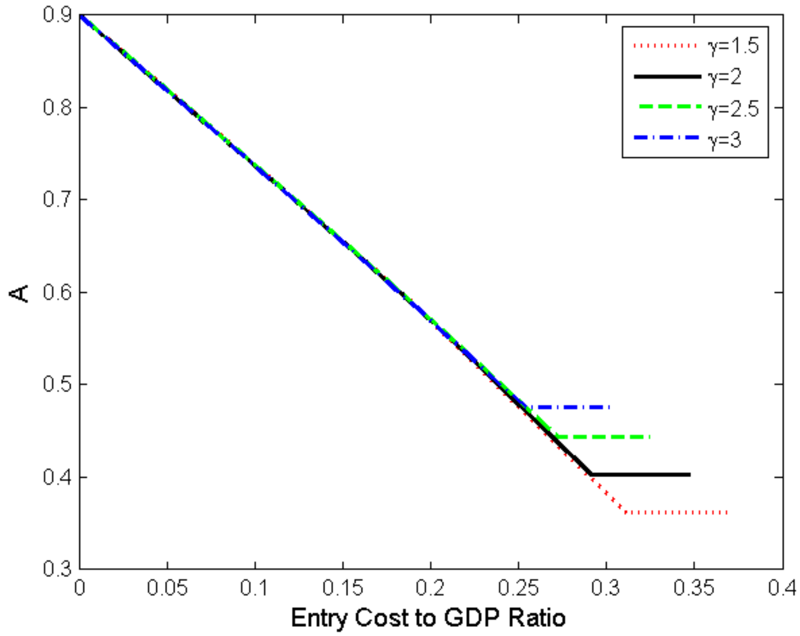


Figure 3 shows that when $\underline{A}$ increases, A^{NE} increases for any given entry cost, and κ_{LC} decreases. This pattern is caused by the general equilibrium effects. Recall that in the symmetric equilibrium without entry, the wage rate equals $\underline{A}$. Hence, as $\underline{A}$ increases, it is more costly to hire labor. It follows that when $\kappa \geq \kappa_{LC}$, the incumbent substitutes labor with a better technology, and therefore A^{LC} increases. Moreover, when $0 \leq \kappa < \kappa_{LC}$, the potential entrant substitutes labor with a better technology, and therefore forces the incumbent to adopt a better technology to block entry. The decrease in κ_{LC} is again caused the increase in A^{LC}.

The sensitivity test for γ is illustrated in figure 4. Similar to the earlier experiments, as γ changes, I recalibrate ϕ^i and ϕ^e. Figure 4 shows that γ has no effects on A^{NE} when $0 \leq \kappa < \kappa_{LC}$. This happens because γ affects the incumbents' and the potential entrants' adoption costs in the same way. However, an increase in γ does lead to an increase in A^{LC} and a decrease in κ_{LC}. To understand this, note that as γ increases, function d becomes less

Figure 4: Effects of γ



convex, and therefore at the margin, it is less costly for the incumbent to adopt a better technology in the limited competition economy, As noted before, the decrease in κ_{LC} is due to the increase in A^{LC}.

To summarize, the numerical examples show that the quantitative effects of entry barriers on technology adoption could be large, and the demand elasticity of the intermediates is the key parameter for the size of this quantitative effects. In particular, the quantitative effects are large when the demand is inelastic and are small when the demand is elastic.

7 Conclusion

This paper has developed a new model to link barriers to entry and technology adoption. In the model, if entry barriers are infinitely large, a small reduction in the barrier will not change the firm's incentive for technology adoption. However, if the entry barriers are below the threshold, a small reduction in the barrier will force the incumbent to adopt a better technology, because the incumbent fears of being replaced by a new firm and losing its monopoly power. Simple calculations based on the model suggests that entry barriers could be a quantitatively important reason for the cross-country differences in TFP and the size of the quantitative effect depends on the demand elasticity. Moreover, the calculations have shown that entry barriers are more harmful in the economy with monopolists facing inelastic demand.

This paper has clearly presented the mechanism through which barriers to entry reduce the technology adopted. But, more serious works are needed to evaluate the quantitative effect of these barriers on productivity. Except the demand elasticity, the quantitative effects of entry barriers on technology adoption may also depend on the development of financial market. In particular, the quantitative effect could be manifested by the financial market imperfection, since it is hard to finance the large entry cost in the economy with less developed financial market.[17] Moreover, since different industries face different size of set-up cost, one can imagine that barriers to entry may have uneven effects on different industries. These subjects are left for future research.

[17] This is related to Erosa and Hidalgo (2008), which find that there are large cross-industry productivity differentials in poor countries and the share of employment in the sectors that need more external financing is positively correlated with the financial market development.

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A Proof of Lemma 1

Lemma 1: For any ϕ^i and ϕ^e, conditional upon the existence of the symmetric equilibrium without entry, there exists κ_{LC}, s.t if $\kappa \geq \kappa_{LC}$, $A^{NE} = A^{LC}$, and if $\kappa < \kappa_{LC}$, $A^{NE} > A^{LC}$.[18]

Proof: A^{NE} in Lemma 1 describes the technology adopted by the incumbent in the symmetric equilibrium without entry. κ_{LC} in Lemma 1 has the form of $\kappa_{LC}(\phi^i, \phi^e) = \max[\underline{A}^{1-\epsilon}(A^{LC})^{\epsilon}(1-\frac{A^{LC}}{A^e_j})-\phi^e d(\underline{A}, A^e_j), 0]$, where A^e_j is determined by $\frac{\underline{A}^{1-\epsilon}(A^{LC})^{1+\epsilon}}{(A^e_j)^2} - \phi^e \frac{\partial d(\underline{A}, A^e_j)}{\partial A^e_j} = 0$.

This lemma can be proved as follows. Step 1 proves that when $\kappa \geq \kappa_{LC}$, the symmetric equilibrium without entry exists and is unique. Moreover, the incumbent adopts A^{LC} in the this equilibrium. Step 2 shows that when $\kappa < \kappa_{LC}$, the incumbent adopts a technology better than A^{LC} in the symmetric equilibrium without entry conditional upon existence.

Step 1: As noted in section 4, when the entry cost is infinity, the incumbent adopts the same technology in the symmetric equilibrium without entry as in the symmetric equilibrium of the limited competition economy. By continuity, this is true as long as κ is large enough so that entry can be blocked when the incumbent upgrade to A^{LC}. In particular, what follows shows that this is true as long as $\kappa \geq \kappa_{LC}$.

Suppose all incumbents upgrade to A^{LC} in the symmetric equilibrium without entry. It follows that $B = A^{LC}$ and $w = \underline{A}$. Conditional upon entry, the potential entrant j solves the following problem:

$$\begin{aligned} \pi^e_j &= \max_{A^e_j, p^e_j} B(p^e_j)^{-\epsilon}(p^e_j - \frac{w}{A^e_j}) - \phi^e d(\underline{A}, A^e_j) \\ s.t. \quad & p^e_j \leq \frac{w}{A^{LC}} \\ & 0 \leq A^e_j \leq A^f \end{aligned}$$

The first order condition for A^e_j is given by:

$$w\frac{B(p^e_j)^{-\epsilon}}{(A^e_j)^2} - \phi^e \frac{\partial d(\underline{A}, A^e_j)}{\partial A^e_j} = 0 \tag{A.1}$$

Inelastic demand implies that the price constraint binds. Substituting $p^e_j = \frac{w}{A^{LC}}$, $B = A^{LC}$

[18] When ϕ^i is sufficiently small or ϕ^e is sufficiently large, κ_{LC} may be zero. In this case, A^{NE} is always equal to A^{LC}.

and $w = \underline{A}$ into the first order condition yields:

$$\frac{\underline{A}^{1-\epsilon}(A^{LC})^{1+\epsilon}}{(A^e_j)^2} - \phi^e \frac{\partial d(\underline{A}, A^e_j)}{\partial A^e_j} = 0 \tag{A.2}$$

The potential entrant's net profit is then given by

$$\pi^e_j - \kappa = \underline{A}^{1-\epsilon}(A^{LC})^{\epsilon}(1 - \frac{A^{LC}}{A^e_j}) - \phi^e d(\underline{A}, A^e_j) - \kappa \tag{A.3}$$

where A^e_j is determined by the above first order condition. When $\kappa \geq \kappa_{LC}$, it is easy to derive $\pi^e_j - \kappa \leq \pi^e_j - \kappa_{LC} \leq 0$.

This proves that when $\kappa \geq \kappa_{LC}$, the incumbent can block entry when upgrading to A^{LC}, and therefore adopts A^{LC} in the symmetric equilibrium without entry. The uniqueness of this equilibrium is guaranteed by the uniqueness of A^{LC}.

Step 2: This part shows that when $\kappa < \kappa_{LC}$, the incumbent chooses a technology better than A^{LC} in the symmetric equilibrium without entry. This is proved by contradiction.

When $\kappa < \kappa_{LC}$, it is easy to show $\pi^e_j - \kappa > \pi^e_j - \kappa_{LC} = 0$. Hence, entry can not be blocked when the incumbent upgrades to A^{LC}. Suppose the symmetric equilibrium without entry exists when $\kappa < \kappa_{LC}$ and the incumbent adopts $A^i < A^{LC}$ in such an equilibrium. It follows that $B = A^i$, $w = \underline{A}$ and $\pi^e_j(A^i, A^i, w) \leq \kappa$.

The incumbent j solves:

$$\begin{aligned}
\pi^B_j \quad &= \quad \max_{A^i_j, p^i_j}[p^i_j B(p^i_j)^{-\epsilon} - w\frac{B(p^i_j)^{-\epsilon}}{A^i_j} - \phi^i d(A_0, A^i_j)] \\
s.t. \quad & \quad \pi^e_j(A^i_j, B, w) - \kappa \leq 0 \\
& \quad p^i_j = \frac{w}{\underline{A}}
\end{aligned}$$

The derivative of the incumbent's objective function with respect to A^i_j is:

$$w\frac{B(p^i_j)^{-\epsilon}}{(A^i_j)^2} - \phi^i \frac{\partial d(A_0, A^i_j)}{\partial A^i_j} \tag{A.4}$$

Substituting $B = A^i$, $w = \underline{A}$ and $p^i_j = \frac{w}{\underline{A}}$ into the above expression and evaluating it at

$A_j^i = A^i$ gives,

$$\frac{\underline{A}}{A^i} - \phi^i \frac{\partial d}{\partial A^i} > \frac{\underline{A}}{A^{LC}} - \phi^i \frac{\partial d}{\partial A^i}|_{(A^i = A^{LC})} = 0 \tag{A.5}$$

The inequality is derived because $A^i < A^{LC}$ and $\frac{\underline{A}}{A^i} - \phi^i \frac{\partial d}{\partial A^i}$ is a decreasing function of A^i. The equality is derived because of (4.2). From section 3, the potential entrant $j's$ profit is decreasing in A_j^i, i.e., $\frac{\partial \pi_j^e(A_j^i, A^i, w)}{\partial A_j^i} < 0$. Hence $\pi_j^e(A_j^i, A^i, w) < \kappa$ for any $A_j^i > A^i$. Let η be a small number. It follows that $\pi_j^e(A^i + \eta, A^i, w) - \kappa < 0$, i.e., the no entry constraint is satisfied when $A_j^i = A^i + \eta$. From (A.5), π_j^B is decreasing around A^i, hence the incumbent can make more profit by adopting $A^i + \eta$ instead of adopting A^i. This contradicts with the assumption that A^i is the technology adopted by the incumbent in the symmetric equilibrium without entry. It follows that the incumbent will not adopt a technology worse than A^{LC} in the symmetric equilibrium without entry. Put differently, if a symmetric equilibrium without entry exists when $\kappa < \kappa_{LC}$, the incumbent will adopt a technology which is better than A^{LC}. QED

B Proof of Proposition 1

The proof of Lemma 1 has showed that for any ϕ^e and ϕ^i, if $\kappa \geq \kappa_{LC}$, the symmetric equilibrium without entry exists and is unique. This part will prove that for any ϕ^i, if $\phi^e \geq \bar{\phi}^e(\phi^i)$, there exists $\kappa_C(\phi^i, \phi^e) \leq \kappa_{LC}(\phi^i, \phi^e)$, such that when $\kappa_C \leq \kappa < \kappa_{LC}$, the symmetric equilibrium without entry exists and is unique. $\kappa_C(\phi^i, \phi^e)$ has the form of $\kappa_C(\phi^i, \phi^e) = \max[\underline{A}^{1-\epsilon}(A_{max}^i)^{\epsilon}(1 - \frac{A_{max}^i}{A_j^e}) - \phi^e d(\underline{A}, A_j^e), 0]$, where A_j^e is determined by $\frac{\underline{A}^{1-\epsilon}(A_{max}^i)^{1+\epsilon}}{(A_j^e)^2} - \phi^e \frac{\partial d(\underline{A}, A_j^e)}{\partial A_j^e} = 0$, and A_{max}^i is determined by $A_{max}^i - \underline{A} - \phi^i d(A_0, A_{max}^i) = 0$. $\bar{\phi}^e(\phi^i)$ has the expression of $\bar{\phi}^e(\phi^i) = (\frac{\epsilon}{\epsilon+1})^2 \frac{\underline{A}^{1-\epsilon}}{(A^{LC})^{1-\epsilon} \frac{\partial d(\underline{A}, A)}{\partial A}|_{(A = \frac{\epsilon+1}{\epsilon} A^{LC})}}$.

Suppose there exists a symmetric equilibrium without entry and in this equilibrium the incumbent adopts A^i, then, $B = A^i$ and $w = \underline{A}$. The potential entrant j solves:

$$\begin{aligned}
\pi_j^e &= \max_{A_j^e, p_j^e} B(p_j^e)^{-\epsilon}(p_j^e - \frac{w}{A_j^e}) - \phi^e d(\underline{A}, A_j^e) \\
s.t. \quad & p_j^e \leq \frac{w}{A_j^i} \\
& 0 \leq A_j^e \leq A^f
\end{aligned}$$

As noted earlier, $p_j^e = \frac{w}{A_j^i}$. Plugging this into the first order condition for A_j^e yields:

$$\frac{\underline{A}^{1-\epsilon} A^i (A_j^i)^\epsilon}{(A_j^e)^2} - \phi^e \frac{\partial d(\underline{A}, A_j^e)}{\partial A_j^e} = 0 \tag{B.1}$$

The potential entrant's profit is given by:

$$\pi_j^e(A_j^i, A^i, w) = \underline{A}^{1-\epsilon} A^i (A_j^i)^{\epsilon-1}(1 - \frac{A_j^i}{A_j^e}) - \phi^e d(\underline{A}, A_j^e) \tag{B.2}$$

Since $0 < \epsilon < 1$, it is easy to show that $\frac{\partial \pi_j^e}{\partial A_j^i} < 0$. In the symmetric equilibrium without entry $A_j^i = A^i$, hence

$$\pi_j^e(A^i, A^i, w) = \underline{A}^{1-\epsilon}(A^i)^\epsilon(1 - \frac{A^i}{A_j^e}) - \phi^e d(\underline{A}, A_j^e) \tag{B.3}$$

where A_j^e is determined by:

$$\frac{\underline{A}^{1-\epsilon}(A^i)^{1+\epsilon}}{(A_j^e)^2} - \phi^e \frac{\partial d(\underline{A}, A_j^e)}{\partial A_j^e} = 0 \tag{B.4}$$

If a symmetric equilibrium without entry exists, then in this equilibrium $\pi_j^e(A^i, A^i, w) \leq \kappa$.

Next I will use four steps to prove the existence and uniqueness. In particular, step 1 proves that the technology adopted by the incumbent in the symmetric equilibrium without entry can not be an A^i s.t $\pi_j^e(A^i, A^i, w) < \kappa$. Step 2 proves that any technology A^i which satisfies $\pi_j^e(A^i, A^i, w) = \kappa$ and $A^i > A^{LC}$ can be supported as a symmetric equilibrium without entry as long as the incumbent makes nonnegative profit by adopting such A^i . Step 3 proves the uniqueness of the A^i defined in step 2. Step 4 proves that when $\kappa_C \leq \kappa < \kappa_{LC}$, the incumbent indeed makes nonnegative profit by adopting the technology defined in the second step.

Step 1: Suppose that there is a symmetric equilibrium without entry in which all the incumbents adopt A^i such that $\pi_j^e(A^i, A^i, w) < \kappa$. Continuity then implies that there exists a small number η, such that $\pi_j^e(A^i - \eta, A^i, w) - \kappa < 0$.

The incumbent in j^{th} industry solves:

$$\begin{aligned}
\pi_j^B &= \max_{A_j^i, p_j^i}[p_j^i B(p_j^i)^{-\epsilon} - w\frac{B(p_j^i)^{-\epsilon}}{A_j^i} - \phi^i d(A_0, A_j^i)] \\
s.t. \quad & \pi_j^e(A_j^i, B, w) - \kappa \leq 0 \\
& p_j^i \leq \frac{w}{\underline{A}}
\end{aligned}$$

Since demand is inelastic, $p_j^i = \frac{w}{\underline{A}}$. The derivative of the objective function with respect to A_j^i is:

$$\frac{B(\underline{A})^{\epsilon} w^{1-\epsilon}}{(A_j^i)^2} - \phi^i \frac{\partial d(A_0, A_j^i)}{\partial A_j^i} \tag{B.5}$$

Substituting $B = A^i$ and $w = \underline{A}$ into the above expression and evaluating it at $A_j^i = A^i$ gives,

$$\frac{\underline{A}}{A^i} - \phi^i \frac{\partial d(A_0, A^i)}{\partial A^i} < \frac{\underline{A}}{A^{LC}} - \phi^i \frac{\partial d(A_0, A^i)}{\partial A^i}|_{A^i = A^{LC}} = 0 \tag{B.6}$$

The inequality holds because from Lemma 1, when $\kappa < \kappa_{LC}$, the incumbent adopts a better technology than A^{LC} in the symmetric equilibrium without entry. The equality holds because of (4.2). Since $\pi_j^e(A^i, A^i, w) - \kappa < 0$ and $\pi_j^e(A^i - \eta, A^i, w) - \kappa < 0$, (B.6) implies that the incumbent j can make more profit by choosing $A_j^i = A^i - \eta$ instead of choosing $A_j^i = A^i$. This contradicts with the assumption that A^i is the technology adopted by the incumbent in the symmetric equilibrium without entry. Therefore, the incumbent will not adopt a technology A^i such that $\pi_j^e(A^i, A^i, w) < \kappa$ in the symmetric equilibrium without entry.

Step 2: Let A^{NE} denote the technology which satisfies $\pi_j^e(A^{NE}, A^{NE}, w) - \kappa = 0$ and $A^{NE} > A^{LC}$. It follows that entry can be blocked if all the incumbents upgrade to A^{NE}. Hence, in order to prove that the symmetric equilibrium without entry exists and in such equilibrium the incumbents upgrade to A^{NE}, I only need to prove that when incumbents in all the other industries upgrade to A^{NE}, the incumbent j will also upgrade to A^{NE} and makes nonnegative profit. The proof follows.

The incumbent j solves:

$$\begin{aligned}
\pi_j^B &= \max_{A_j^i, p_j^i}[p_j^i B(p_j^i)^{-\epsilon} - w\frac{B(p_j^i)^{-\epsilon}}{A_j^i} - \phi^i d(A_0, A_j^i)] \\
s.t. \quad & \pi_j^e(A_j^i, B, w) - \kappa \leq 0 \\
& p_j^i \leq \frac{w}{\underline{A}}
\end{aligned}$$

Inelastic demand implies $p_j^i = \frac{w}{\underline{A}}$. The derivative of the objective function with respect to A_j^i is:

$$\frac{B(\underline{A})^{\epsilon} w^{1-\epsilon}}{(A_j^i)^2} - \phi^i \frac{\partial d(A_0, A_j^i)}{\partial A_j^i} \tag{B.7}$$

As in the first step, the following inequalities hold for all $A_j^i > A^{NE}$:

$$\begin{aligned} &\frac{B(\underline{A})^{\epsilon} w^{1-\epsilon}}{(A_j^i)^2} - \phi^i \frac{\partial d(A_0, A_j^i)}{\partial A_j^i} < \frac{B(\underline{A})^{\epsilon} w^{1-\epsilon}}{(A^{NE})^2} - \phi^i \frac{\partial d(A_0, A_j^i)}{\partial A_j^i}|_{A_j^i = A^{NE}} \\ &= \frac{\underline{A}}{A^{NE}} - \phi^i \frac{\partial d(A_0, A^i)}{\partial A^i}|_{A_j^i = A^{NE}} < \frac{\underline{A}}{A^{LC}} - \phi^i \frac{\partial d(A_0, A^i)}{\partial A^i}|_{A_j^i = A^{LC}} = 0 \end{aligned} \tag{B.8}$$

The first inequality is derived since $\frac{B(\underline{A})^{\epsilon} w^{1-\epsilon}}{(A_j^i)^2} - \phi^i \frac{\partial d(A_0, A_j^i)}{\partial A_j^i}$ is a decreasing function in A_j^i. The first equality is derived by substituting $B = A^{NE}$ and $w = \underline{A}$ into $\frac{B(\underline{A})^{\epsilon} w^{1-\epsilon}}{(A^{NE})^2} - \phi^i \frac{\partial d(A_0, A_j^i)}{\partial A_j^i}|_{A_j^i = A^{NE}}$. The second inequality holds because $\frac{\underline{A}}{A^{NE}} - \phi^i \frac{\partial d(A_0, A^i)}{\partial A^i}|_{A_j^i = A^{NE}}$ is a decreasing function in A^{NE} and $A^{NE} > A^{LC}$. The second equality holds because of (4.2).

Since $\pi_j^e(A^{NE}, A^{NE}, w) - \kappa = 0$ and $\frac{\partial \pi_j^e(A_j^i, A^{NE}, w)}{\partial A_j^i} < 0$, $\pi_j^e(A_j^i, A^{NE}, w) - \kappa > 0$ if $A_j^i < A^{NE}$ and $\pi_j^e(A_j^i, A^{NE}, w) - \kappa < 0$ if $A_j^i > A^{NE}$. (B.8) then implies that the incumbent $j's$ profit is decreasing in A_j^i when $A_j^i \geq A^{NE}$, and therefore the incumbent j wants to adopt a technology level as low as possible. But to block entry, the incumbent j must adopt a technology at least as good as A^{NE}, and therefore will indeed choose $A_j^i = A^{NE}$. This proves that if all the other incumbents choose A^{NE}, the incumbent j will also choose A^{NE}. Hence as long as the incumbent makes nonnegative profit when adopting A^{NE}, the symmetric equilibrium without entry exists and in such an equilibrium, the incumbent upgrades to A^{NE}.

Step 3: To prove the uniqueness of the symmetric equilibrium without entry when $\kappa_C \leq \kappa < \kappa_{LC}$, I only need to prove the uniqueness of A^{NE}.

Evaluating the left of (B.4) at $A_j^e = \frac{\epsilon+1}{\epsilon} A^i$ gives:

$$\begin{aligned} &(\frac{\epsilon}{\epsilon+1})^2 \underline{A}^{1-\epsilon} (A^i)^{\epsilon-1} - \phi^e \frac{\partial d(\underline{A}, A_j^e)}{\partial A_j^e}|_{A_j^e = \frac{\epsilon+1}{\epsilon} A^i} \\ < \quad &(\frac{\epsilon}{\epsilon+1})^2 \underline{A}^{1-\epsilon} (A^{LC})^{\epsilon-1} - \phi^e \frac{\partial d(\underline{A}, A_j^e)}{\partial A_j^e}|_{A_j^e = \frac{\epsilon+1}{\epsilon} A^{LC}} < 0 \end{aligned} \tag{B.9}$$

The first inequality holds because the first expression is decreasing in A^i, and when $\kappa < \kappa_{LC}$, the incumbents' equilibrium technology is bigger than A^{LC}. The second inequality holds because $\phi^e > \bar{\phi}^e$. Since the left of (B.4) is decreasing in A_j^e, (B.9) implies that $A_j^e < \frac{\epsilon+1}{\epsilon}A^i$. Applying envelop theory to (B.3) gives

$$\frac{\partial \pi_j^e(A^i, A^i, w)}{\partial A^i} = \underline{A}^{1-\epsilon}(A^i)^{\epsilon-1}\epsilon(1 - \frac{\epsilon+1}{\epsilon}\frac{A^i}{A_j^e}) < 0 \tag{B.10}$$

The inequality holds because $A_j^e < \frac{\epsilon+1}{\epsilon}A^i$. (B.10) then implies that $\pi_j^e(A^i, A^i, w)$ is a decreasing function of A^i, and therefore A^{NE} is unique.

Step 4: From step 1 and step 2, the symmetric equilibrium without entry is determined by $\pi_j^e(A^{NE}, A^{NE}, w) - \kappa = 0$, i.e.,

$$\underline{A}^{1-\epsilon}(A^{NE})^{\epsilon}(1 - \frac{A^{NE}}{A_j^e}) - \phi^e d(\underline{A}, A_j^e) - \kappa = 0 \tag{B.11}$$

where A_j^e is determined by the potential entrant's first order condition (B.4). From (B.10), the left of (B.11) is decreasing in A^{NE}. Applying implicit function theorem to (B.11) and (B.4) gives $\frac{\partial A^{NE}}{\partial \kappa} < 0$.

In the symmetric equilibrium without entry, the incumbent's profit is $\pi_j^B = A^{NE} - \underline{A} - \phi^i d(A_0, A^{NE})$. It is easy to derive:

$$\frac{\partial \pi_j^B}{\partial A^{NE}} = 1 - \phi^i \frac{\partial d(A_0, A^{NE})}{\partial A^{NE}}$$

When $A^{NE} = A^{LC}$, comparing the above expression with (4.2), it is easy to derive that $\frac{\partial \pi_j^B}{\partial A^{NE}}|_{A^{NE}=A^{LC}} > 0$. Because I assume that the incumbent makes nonnegative profit when adopting A^{LC}, it follows that the incumbent's profit is nonnegative when $\kappa = \kappa_{LC}$. As κ decreases from κ_{LC}, A^{NE} increases, and π_j^B increases first, and then at some point π_j^B begins to decrease. This implies that there is a A_{max}^i, such that when $A^{NE} \leq A_{max}^i$, $\pi_j^B \geq 0$.

Let κ_1 be the value of κ which induces $A^{NE} = A_{max}^i$. $\frac{\partial A^{NE}}{\partial \kappa} < 0$ implies that $\pi_j^B \geq 0$ if $\kappa \geq \kappa_1$. Let $\kappa_C = \max[\kappa_1, 0]$. Then, if $\kappa \geq \kappa_C$, $\pi_j^B \geq 0$. Since the incumbent has nonnegative profit when $\kappa = \kappa_{LC}$, it follows that $\kappa_C \leq \kappa_{LC}$ when $\kappa_{LC} > 0$, and $\kappa_C = \kappa_{LC} = 0$ when $\kappa_{LC} = 0$. $\kappa_{LC} = 0$ is not a very interesting case, so in this paper, I will assume $\kappa_{LC} > 0$.

The above proof only considers the case in which both the incumbent's and the potential entrant's choice of technology are interior. If either of them is a corner solution, it is easy to generalize the above proof and all the results still hold. QED

C Proof of Corollary 1

Since $\kappa \geq 0$, $\phi^e \geq \phi^i$, $A_0 > \underline{A}$ and d is strictly decreasing in its first argument, the incumbent can always adopt the same technology as the potential entrant and makes more profit than the potential entrant. This implies that entry can always be blocked, and a symmetric equilibrium with entry can never exist.

Based on the proof of Proposition 1, to prove Corollary 1, I only need to show that $\kappa_C = 0$ when $\phi^e \geq \phi^i$. From step 4 of the proof of Proposition 1, this is the same as to prove that for any $\kappa \geq 0$, the incumbent can always make nonnegative profit by adopting A^{NE}, where A^{NE} satisfies $\pi^e_j(A^{NE}, A^{NE}, w) - \kappa = 0$. The proof is as follows.

$\pi^e_j(A^{NE}, A^{NE}, w) - \kappa = 0$ implies that $\forall \kappa \geq 0$, when all the incumbents adopt A^{NE}, the potential entrant j makes 0 profit after paying the entry cost. Hence the incumbent j will make nonnegative profit by adopting the same technology A^e_j as the potential entrant j. From step 2 of the proof of Proposition 1, A^{NE} is the incumbent $j's$ optimal choice if all the other incumbents choose A^{NE}. This implies that the incumbent j makes more profit by adopting A^{NE} than adopting A^e_j, and therefore makes nonnegative profit by adopting A^{NE}. This proves that for any κ, a symmetric equilibrium without entry exists when $\phi^e \geq \phi^i$. Note that if $\phi^e > \bar{\phi}^e$, this equilibrium is also unique. QED

D Proof of Proposition 2

The proof of proposition 1 shows that the symmetric equilibrium without entry exists when $\kappa_C \leq \kappa < \kappa_{LC}$. Proposition 2 then follows directly from Lemma 1.

E Proof of Proposition 3

The equilibrium in the limited competition economy is determined by:

$$1 - \frac{A^i}{\underline{A}} \phi^i \frac{\partial d(A_0, A^i)}{\partial A^i} = 0 \tag{E.1}$$

From the above equation, it is clear to see that the first part of proposition 3 is true.

When $\kappa_C \leq \kappa < \kappa_{LC}$, from the proof of proposition 1, the symmetric equilibrium without entry can be represented by:

$$F(A^i, A^e_j) = 0 \tag{E.2}$$
$$G(A^i, A^e_j) = 0 \tag{E.3}$$

where the two functions F and G are defined by:

$$F(A^i, A^e_j) = \underline{A}^{1-\epsilon}(A^i)^{\epsilon}(1 - \frac{A^i}{A^e_j}) - \phi^e d(\underline{A}, A^e_j) - \kappa \tag{E.4}$$
$$G(A^i, A^e_j) = \frac{\underline{A}^{1-\epsilon}(A^i)^{1+\epsilon}}{(A^e_j)^2} - \phi^e \frac{\partial d(\underline{A}, A^e_j)}{\partial A^e_j} \tag{E.5}$$

Straightforward calculations allows one to derive and sign the partial derivatives of the F and G functions as follows: $F_{A^i} < 0$ as derived in the proof of proposition 1, $F_{A^e_j} = 0$, $G_{A^i} = (1+\epsilon)\frac{\underline{A}^{1-\epsilon}(A^i)^{\epsilon}}{(A^e_j)^2} > 0$, $G_{A^e_j} = -2\frac{\underline{A}^{1-\epsilon}(A^i)^{1+\epsilon}}{(A^e_j)^3} - \phi^e \frac{\partial^2 d(\underline{A}, A^e_j)}{\partial (A^e_j)^2} < 0$, $F_\kappa = -1 < 0$, $G_\kappa = 0$, $F_{\phi^i} = 0$, $G_{\phi^i} = 0$, $F_{\phi^e} = -d(\underline{A}, A^e_j) < 0$ and $G_{\phi^e} = -\frac{\partial d(\underline{A}, A^e_j)}{\partial A^e_j} < 0$.

Standard analysis implies that comparative statics results are given by:

$$\frac{\partial A^i}{\partial \kappa} = -\frac{F_\kappa G_{A^e_j} - G_\kappa F_{A^e_j}}{F_{A^i} G_{A^e_j} - F_{A^e_j} G_{A^i}} = -\frac{F_\kappa G_{A^e_j}}{F_{A^i} G_{A^e_j}} < 0 \tag{E.6}$$

$$\frac{\partial A^i}{\partial \phi^i} = -\frac{F_{\phi^i} G_{A^e_j} - G_{\phi^i} F_{A^e_j}}{F_{A^i} G_{A^e_j} - F_{A^e_j} G_{A^i}} = -\frac{F_{\phi^i} G_{A^e_j}}{F_{A^i} G_{A^e_j}} = 0 \tag{E.7}$$

$$\frac{\partial A^i}{\partial \phi^e} = -\frac{F_{\phi^e} G_{A^e_j} - G_{\phi^e} F_{A^e_j}}{F_{A^i} G_{A^e_j} - F_{A^e_j} G_{A^i}} = -\frac{F_{\phi^e} G_{A^e_j}}{F_{A^i} G_{A^e_j}} < 0 \tag{E.8}$$

QED

F Proof of Proposition 4

Proof: Conditional upon entry, the potential entrant j solves:

$$\max_{A_j^e, p_j^e} [p_j^e B(p_j^e)^{-\epsilon} - w\frac{B(p_j^e)^{-\epsilon}}{A_j^e} - \phi^e d(\underline{A}, A_j^e)]$$

$$s.t. \qquad p_j^e \leq \frac{w}{A_j^i}$$

$$0 \leq A_j^e \leq A^f$$

As noted earlier, the potential entrant j will necessarily set $p_j^e = \frac{w}{A_j^i}$. It is easy to show that the above objective function is strictly concave in A_j^e for given values of B, w and A_j^i, hence, if the solution for A_j^e is interior, it is unique and determined by the first order condition. Substituting $p_j^e = \frac{w}{A_j^i}$ into the incumbent's first order condition for A_j^e yields:

$$\frac{B(A_j^i)^{\epsilon} w^{1-\epsilon}}{(A_j^e)^2} - \phi^e \frac{\partial d(\underline{A}, A_j^e)}{\partial A_j^e} = 0$$

In the symmetric equilibrium with entry, $A_j^e = A^e$ and $A_j^i = A_0$ for all j. Similar to that in the symmetric equilibrium without entry, in the symmetric equilibrium with entry, $B = A^e$ and $w = A_0$. Plugging those conditions into the above first order condition gives:

$$1 - \frac{A^e}{A_0}\phi^e \frac{\partial d(\underline{A}, A^e)}{\partial A^e} = 0 \tag{F.1}$$

Let A^E be the entrant's technology in the symmetric equilibrium with entry. Similar to the argument in section 4, the strict convexity of d implies that if A^E is interior, it is unique and determined by (F.1), otherwise, it is A^f.[19]

There are two additional conditions that must be satisfied to guarantee the existence of the symmetric equilibrium with entry. The first condition is that the potential entrant's profit is nonnegative, i.e., $A^E - A_0 - \phi^e d(\underline{A}, A^E) - \kappa \geq 0$. The second condition is that it is not optimal for the incumbent to block entry, i.e., $\pi_j^B \leq 0$.

For a given positive ϕ^i, when $\phi^e = 0$ and $\kappa = 0$, it is easy to see that the symmetric equilibrium with entry exists. To see this, note that since the adoption cost is zero, the

[19]Note that A^E must be greater than A_0, since otherwise, entry can be blocked.

potential entrant operates at the technology frontier automatically and has profit $A^f - A_0$, hence the first condition is satisfied. Moreover, it is impossible for the incumbent to block entry. Since the best the incumbent can do is to adopt the frontier technology too. However, when both firms adopt frontier technology, they both make 0 profits at the third stage, and therefore the incumbent has losses because it has to pay the updating cost. It follows that the second condition is satisfied. This proves that the symmetric equilibrium with entry exists for a given positive ϕ^i if $\phi^e = 0$ and $\kappa = 0$.

Now, suppose only $\kappa = 0$, then, continuity implies that there is a $\hat{\phi}^e$ such that the symmetric equilibrium with entry exists for all $\phi^e < \hat{\phi}^e$. For a given $\phi^e < \hat{\phi}^e$, since the symmetric equilibrium with entry exists when $\kappa = 0$, continuity then implies that there is a $\hat{\kappa}$, such that the symmetric equilibrium with entry exists for all $\kappa < \hat{\kappa}$. This proves the existence of the symmetric equilibrium with entry. The uniqueness of this equilibrium is guaranteed by the uniqueness of A^E. QED

G Proof of Proposition 5

If the symmetric equilibrium with entry exists, it is determined by (F.1). From (F.1), it is easy to see that A^E is decreasing in ϕ^e and does not depend on κ and ϕ^i. QED